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Evaluation of high-strength steel SA-517-Gr-F for large pressure vessels

Conventionally, carbon steel material has been widely used around the globe for the fabrication of static equipment—such as tall towers, vessels, heat exchangers, etc.—for less-corrosive service. This material is generally procured in a normalized or quenched and tempered condition to gain benefits towards an exemption from impact test requirements and to obtain a refined grain structure.

In this work, the effect of using a high-strength, low-alloy material SA-517-Gr-F has been studied as an alternative to the conventionally used carbon steel SA-516-Gr-60/70, specifically for large towers in a seismic prone zone and extreme weather conditions. The composition of SA-517-Gr-F is ¾ nickel (Ni)-½ chromium (Cr)-½ molybdenum (Mo-V). The alloying elements are present in very low percentages and this material has a very high mechanical strength. Therefore, it is termed as high-strength, low-alloy steel. The composition of SS 304L is 18 Cr-8 Ni. The alloying elements are present in higher percentages, which improves their corrosion resistance property against SA-517-Gr-F.

In this work, literature on the use of SA-517-Gr-F has been checked in terms of machinability and fabrication, along with commercial factors. Also, fabrication challenges and limitations have been identified by consulting renowned pressure vessel fabricators.

SA-517-Gr-F is a high-strength alloy material that can be explored as an alternative to normal carbon steel (SA-516-Gr-60/70) owing to its very high ultimate tensile strength and, therefore, its higher allowable stresses. TABLE 1 presents further details. These allowable stresses remain constant for a wide range of temperatures. The difference in thicknesses between SA-517-Gr-F and SA-516-Gr-70 are in the range of 50%–80%, based on design temperature. Recently, the application of SA-517-Gr-F seems to be limited in the industry. The constraints that limit the use of this material have been studied technically as well as commercially.

In this work, the use of SA-517-Gr-F has been holistically explored, and conclusions and key observations have been detailed.

Discussion. The selection of appropriate material of construction (MOC) for the design and fabrication of any pressure vessel is crucial. These are regulated by many factors, including:

- Type of service
- Fluid in contact
- Corrosivity of the fluid
- External environmental factors
- Availability of the material
- Economics (cost of the equipment)
- Overall weight
- Machinability and weldability of material.

The most widely used MOC in the design and fabrication of static equipment is carbon steel—SA-516-Gr-70 (ASME SEC II Part D).[1] However, in specific cases, SA-517-Gr-F (ASME SEC II Part D)—an alternative for SA-516-Gr-70—should be evaluated for reduction in thicknesses and optimization in overall weight. This leads to an overall reduction in associated costs like logistics, transportation, installation (erection) and required civil structure or foundation.

SA-517-Gr-F is evaluated for static equipment with a base MOC of carbon steel and:

- Large static equipment (specifically, large inside diameter)
    - Spheres
    - Large process columns
    - Reactors
- High-pressure equipment
- High-temperature service
- Very high external loads, wind or seismic.

INLFUENCING FACTORS

Type of service. It is imperative to match the most optimal MOC with the type of the service handled by the equipment.

TABLE 1. Comparison of SA-516-70 and SA-517-Gr-F

Parameters	SA-516-Gr-70	SA-517-Gr-F
Type	Carbon steel	Low-alloy, high-strength
		¾Ni-½Cr-½Mo-V
Uns	K02700	K11576
Size limitation	No limitation	Available up to 65 mm only
P no.	1	11 b
PWHT requirement	Mandatory over 38 mm	Mandatory over 15 mm
Minimum tensile strength	485 MPa	795 MPa
Minimum yield strength	260 MPa	690 MPa

This can be classified as sour [wet hydrogen sulfide (H_2S)], amine, caustic, etc.[2] Numerous allied factors exist, such as the nature of the fluid's corrosivity in contact with the inner surfaces of the equipment.

SA-517-Gr-F can withstand mild corrosive applications with a suitable internal corrosion allowance, depending on the anticipated rate of corrosion of the metal due to the specific fluid in contact. SA-516-Gr-60/70 can also handle mild corrosive applications, such as hydrocarbons with lower partial pressure of hydrogen (H_2).

For carbon steel, a corrosion allowance of 3 mm–6 mm is considered, depending on the contact fluid and the yearly corrosion rate. However, since SA-517-Gr-F has alloying elements, a lower corrosion allowance is available compared to carbon steel.

Environmental factors. External environmental factors, such as the site location based on its proximity to coastal/marine areas, regulate proper MOC selection to mitigate accelerated external corrosion.[3,4,5] This is accomplished by an external corrosion allowance or even with coating/painting on the external surfaces of the affected equipment.

Availability and expertise. While choosing the appropriate MOC for the given process application, extra attention must be paid to the availability of the chosen MOC and the expertise needed to handle it across various global fabricators.

Economics and overall weight. The overall fabrication and operating weight of the equipment is crucial, particularly for large equipment. Equipment weight is directly proportional to the thicknesses required based on design conditions. The equipment's total investment cost (TIC) comprises:

- Design and engineering cost
- Fabricated weight
- Raw material cost
- Material handling/fabrication allowance
- Associated cost of material and equipment inspection and testing
- Logistics cost
- Installation or erection cost
- Fabricated weight of equipment determines its overall cost
- Fabricated weight of equipment is also significant to determine optimum allied costs like transportation and erection costs
- Operating weight of the equipment determines the overall civil foundation/structure cost
- Thicknesses and weights are a function of the allowable stresses of the selected MOC.

Therefore, overall weight and associated equipment costs are related to correct MOC selection.

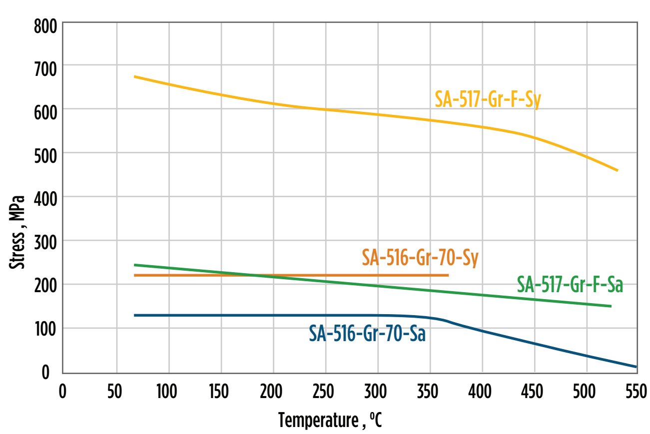

FIG. 1. Yield stress (SY) and allowable stress (SA) variation.

Material machinability and weldability. It is evident that SA-517-Gr-F is characterized by very high tensile and mechanical strength, making the material quite strong, hard and challenging to handle, weld, form, roll and fabricate. During fabrication, steady heating is required for smooth leak-proof joints.

This material also has stringent impact testing and post-weld heat treatment (PWHT) requirements compared to SA-516-Gr-70.

Unlike SA-516-Gr-70, SA-517-Gr-F may also require:

- Vacuum gas while procuring the raw material plate
- Simulated PWHT of mechanical test coupons
- High-temperature tension test, a supplementary requirement in case of high operating temperature
- Post-heating requirement.

COMPARISON OF SA-516-GR-70 VS. SA-517-GR-F

TABLE 1 summarizes the differences in SA-516-Gr-70 and SA-517-Gr-F across various important parameters, ranging from mechanical strength and testing requirements to material costs.

Approach. Detailed design calculations were performed for a specific group of static equipment (**FIG. 1**). These included three nos. large towers (low pressure and large diameters) and two nos. high-pressure spheres (with large diameters).

These calculations were performed in two cases for each piece of equipment:

- Case 1 with SA-516-Gr-70 as the base material
- Case 2 with SA-517-Gr-F as the base material.

A globally recognized and widely used design tool[a] was used to perform these calculations. The equipment was analyzed for the following design conditions:

- Internal pressure and temperature
- External pressure and temperature
- External loading due to wind (unidirectional wind force causing shear force and bending moment)
- External loading due to seismic condition (a transverse inertial force that was analyzed considering the vertical tower as the cantilever system with a lumped mass).

The site location was highly prone to earthquakes, so seismic external loading conditions and internal pressure governed thickness requirements.

Thickness calculation. The pressure vessel thickness calculation formula finds its basis in the thickness evaluation formula of the pressure vessel for the generated hoop stress. The hoop stress formula (cylindrical hoop stress) is shown in Eq. 1:

$$\sigma_H = \frac{Pd}{2t} \qquad (1)$$

where:

σ_H = cylinder hoop stress in Pa
P = internal pressure in Pa
d = cylinder inside diameter, m
t = wall thickness, m

As per ASME Section VIII Div.1,[6] the thickness of the cylindrical shell can be calculated using (in circumferential stress) Eq. 2:

$$t = \frac{PR}{SE-0.6P} \text{ or } P = \frac{SEt}{R+0.6t} \qquad (2)$$

As per ASME Section VIII Div.1, the thickness of the spherical shell can be calculated using Eq. 3:

$$t = \frac{PR}{2SE-0.2P} \text{ or } P = \frac{2SEt}{R+0.2t} \qquad (3)$$

where:

t = minimum required thickness of shell
P = internal design pressure
R = inside radius of the shell course under consideration
S = maximum allowable stress value of the shell material
E = joint efficiency.

It can be seen from the above formulae that, conceptually, the thickness requirement is inversely proportional to the allowable stress value of the material. The higher the allowable stress value of the material, the lower the thickness required for the given design conditions of the equipment under consideration, and vice versa.

Analyses. Of the five design analyses performed, the results of comparisons of thickness, cost, civil (foundation) forces, etc., for one large tower are presented when analyzed in SA-516-Gr-70 and SA-517-Gr-F for the same conditions.

Technical specifications of the tower:

- Base MOC: SA-516-Gr-70
- Alternate MOC: SA-517-Gr-F
- Design pressure: 9.5 barg
- Design temperature: 120°C/–46°C
- Dimensions: ~ 10.5-m inside diameter, x ~ 100 m
- Skirt length: ~ 5 m
- Design code: ASME Section VIII Div. 1.

The comparison results have been populated in **FIG. 2** and **TABLE 2.**

Results. The following parameters were compared based on the aforementioned analysis:

- Thickness requirement
- Fabricated steel weight
- Operating weight
- Seismic shear force and bending moment

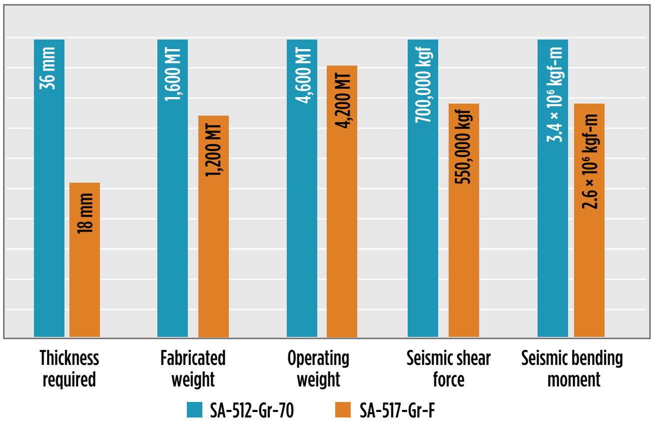

FIG. 2. Comparison plot between various calculation results.

TABLE 2. Comparison of results between SA-516-70 and SA-517-Gr-F

Parameters	SA-516-Gr-70	SA-517-Gr-F
Thickness required, range (mm)	36–44	18–30
Fabricated weight, MT	1,600	1,200
Operating weight, MT	4,600	4,200
Seismic shear force, kg-f	700,000	550,000
Seismic bending moment, kgf-m	34,000,000	26,000,000
Equipment supply cost	The equipment supply cost is almost the same in cases of SA-516-Gr-70 and SA-517-Gr-F. The savings in the equipment weight in the case of SA-517-Gr-F has been nullified, owing to the high material handling cost as compared to SA-516-Gr-70.	
Equipment installation cost	The installation cost of the equipment is reduced by almost 30% in the case of SA-517-Gr-F vs. SA-516-Gr-70 due to significant reduction in equipment weight.	
Foundation related cost	Due to the reduced foundation loads (seismic shear force and seismic bending moment), a reduction in the range of 10% is observed in the piling requirement in the case of SA-517 Gr-F vs. SA-516-Gr-70	

Is this installation's cost reduction a result of reduced thickness alone or has the additional cost that arises with fabrication risk and fabrication specialization required for SA-517 been accounted for?

The reduction in installation cost is a result of reduced erection weight owing to reduced thicknesses in the case of SA-517-Gr-F (due to high mechanical strength of the material). Fabrication and handling costs are considered while deriving the actual capital cost of the equipment.

- Overall equipment cost

For towers, the results can be interpreted as:

SA-517-Gr-F is a good alternative for equipment with larger sizes, high pressures and heavy external loads that may lead to overall cost optimization. Designers must be cautious, as the material comes with fabrication challenges.

- Weight reduction: ~ 35%–40%
- Seismic force and moment reduction: ~ 30%–35%
- Equipment cost optimization: ~ 10%
- Civil foundation/structure cost optimization: ~ 10% of equipment cost
- Installation cost optimization: ~ 20%

For spheres, the results can be interpreted as follows:

- Weight reduction: 35%–40%
- Seismic force and moment reduction: ~ 35%–40%
- Equipment cost optimization: ~ 10%
- Civil foundation/structure cost optimization: ~ 10% of the equipment cost
- Installation cost optimization: ~ 20%

Challenges in using SA-517-GR-F. Although it appears that the use of SA-517-Gr-F in static equipment can lead to significant savings in terms of steel and foundation costs, etc., its use also presents a few challenges:

- **Material availability**—The availability of this material is limited, which can pose a threat to the project schedule. Sourcing and pricing of this material should be studied well in advance.
- **Material handling**—Expertise is needed from the fabricator to handle such hard material—specifically for greater diameters and thicknesses—as know-how and expertise in this area can be quite limited among global static equipment suppliers.
- **Application limitation.** The use of this material cannot be extended to hydrogen service (e.g., hydrogen mounded bullets). Equipment in hydrogen service calls for a hardness limitation requirement (e.g., 235 BHN). This cannot be fulfilled with a low-alloy, high-strength material like SA-517-Gr-F.

Takeaway. When evaluated, SA-517-Gr-F can be a key alternative for critical static equipment with a base MOC like SA-516-Gr-70, with certain conditions. Considering the challenges in sourcing and handling SA-517-Gr-F, its use may be restricted to static equipment such as spheres, towers and reactors with very large-diameter, high-pressure and high-temperature requirements. The use of this material (to a larger extent) is governed by site/plant location, which must be explored and evaluated to ensure proper soil hardness and exposure to severe external loads (wind, seismic, etc.), as well as extended to scenarios where the optimization of the civil foundation (piling) requirements becomes crucial.

When SA-517-Gr-F must be used in any project with critical static equipment, its sourcing must be well planned and ahead of schedule.

It is prudent for the design engineer to consider all important parameters—such as equipment type, design conditions, installation site conditions, availability and handling of SA-517-Gr-F, as well as reliability—before selecting SA-517-Gr-F as an alternative to carbon steel SA-516-Gr-70.

The raw material cost of SA-517-Gr-F is approximately 30% more expensive than SA-516-Gr-70, and the raw material handling and fabrication of SA-517-Gr-F is higher than SA-516-Gr-70. However, due to the overall reduction in weight, civil foundation forces, transportation and erection costs, the capital investment for SA-517-Gr-F could prove more lucrative in specific cases, such as when equipment experiences high pressure and/or temperatures, extreme external shear force and bending moments due to wind or earthquake. Process fluids are compatible with SA-517-Gr-F, when viewed as a substitute for SA-516-Gr-70. HP

NOTE

[a] Hexagon PPM's PVElite-2019

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